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DAMAGE : experimental validation and prospects

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Abstract

The purpose is to present DAMAGE, a software devoloped by LMT-Cachan and supported by SNECMA Space Engine Division. Based on the LMT two-scale model, this software is dedicated to the prediction of HCF crack initiation, especially for high stress ratios and multiaxial loading. The experimental validation of DAMAGE on industrial applications will be presented and disscussed.

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Keywords : multiaxial Fatigue; Lifetime prediction; Damage

1. Introduction

In service, spaces engines components are submitted to loadings that may imply high multiaxiality and complex history. Characteristics of those loadings are high load ratio, small amplitude solicitations due to vibrations (High Cycle Fatigue) but also high amplitude solicitations applied when the engine is started and shut down (Low Cycle Fatigue). A damage model based on the Lemaitre's damage law [1] gives a good response in the case of Low Cycle Fatigue when plasticity and damage may be observed at the scale of the structure (macro-scale). When the structure is submitted to low amplitude solicitations, for instance vibrations, the material behaviour remains elastic at the macro-scale. However failure finally occurs due to micro-plasticity and micro-damage that leads to the initiation of a macrocrack. A two-scale damage approach has been developed in LMT Cachan in order to solve the problem of lifetime prediction in the HCF domain [2–4].

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2. A two scale model for lifetime prediction

Continuum damage mechanics is a powerfull tool to predict crack initiation in a structure under multiaxial and random loadings. It handles as well monotonic and cyclic solicitations. Based on the concept of effective stress, Lemaitre [1] developed a thermodynamic framework that gathers elasticity, plasticity and damage equations. The incremental resolution of those equations gives access to the evolution of some internal variables that represent the material state. However, the model introduces a damage evolution driven by plasticity (and enhanced by the stress triaxiality). Thus lifetime prediction can be done under LCF conditions but is not straight forwardly possible under HCF conditions (when the structure remains elastic). A two-scale approach has been then developed to tackle this difficulty [2–4]. This approach consists on performing a simple elastic (eventually elasto-plastic) calculation on the geometry of the studied structure (macro scale). The local stress, strain, plastic strain and temperature fields are taken at the most critical points to design considerations. Those fields are applied to a Relevant Volume Element (meso scale) that contains a certain number of defects. Those defects are gathered in a virtual inclusion (micro scale).

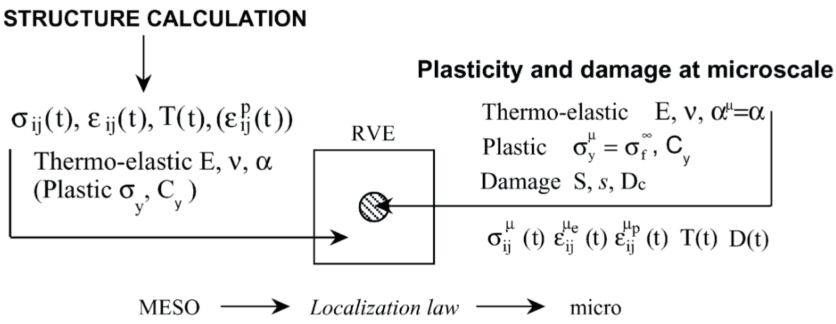

Figure 1 : Scale transition concept [4]

- The material behavior at the meso scale is the behavior observed at the macroscopique level. Under pure HCF conditions, the meso scale is thermo-elastic.
- At the micro scale, damage is coupled with an elasto-plastic behavior. Micro plasticity is supposed to be activated below the macro elastic limit. The micro elastic limit is then taken equal to the fatigue limit.

The constitutive equations are integrated incrementally at the inclusion level. When the damage reaches a critical value, the inclusion is supposed to be broken and a macro crack is initiated. Critical damage D_c is conventionally taken equal to 0,2 or 0,3 for metallic materials because it corresponds to the maximum value of stiffness loss observable in a monotonic tensile test. The model damage parameters s,S and the asymptotic fatigue limit σ_f^∞ are identified from a uniaxial tensile fatigue curve. The implementation of the model has been done in a code written in Fortran. A python graphic interface is provided and includes a mode for fast identification procedure. Loadings are described as blocks (5000 points maximum) that can be repeated. A classic computation over 10^7 cycles on a personal computer use only one processor takes only few minutes to be done.

4. Experimental campaign

The presented experimental results gather informations obtained during the G. Barbier phD thesis [5] and the current phD thesis of P. Gaborit. The aim of the experimental campaign is to provide validation cases on representative multiaxial loadings to quantify the performance of the model. The experiments have been carried out on cross-shaped samples for which the reader can find the drawing in [6]. The samples are 5mm thick and thinned in the center to a thickness of 1mm.

Figure 2 : Thinned cross shape sample

The test is performed by using a triaxial test machine at the lab LMT Cachan [7] that has three axes but is used in the present case in the horizontal plane. The four actuators can deliver a maximum load of 100kN and two actuators on the same axis are controlled as a pair. Loading is then applied in term of difference and average load (or displacement) on each load axis.

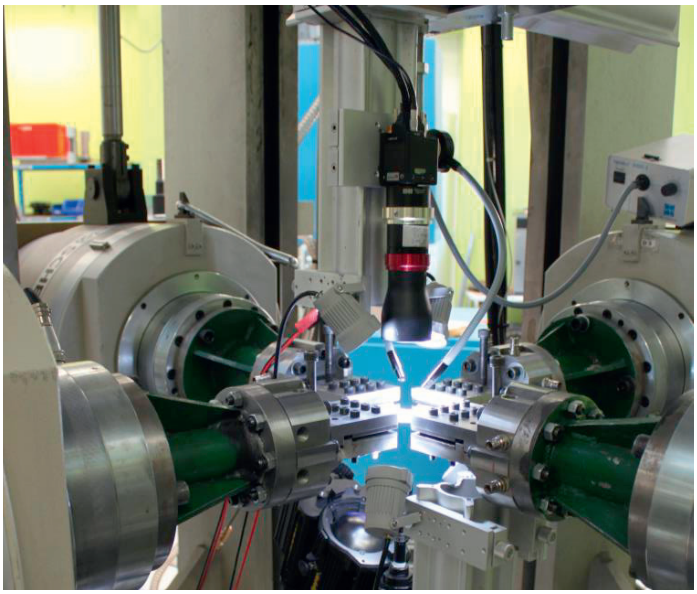

Figure 3 : Experimental setup

Two cameras PCO pixelfly are used with G1 telecentric lenses. They observe on both faces of the sample the center of the sample over an area of about 1cm^2. The sample is covered with white paint and black dots. Digital image correlation (DIC) is then used to calculate the displacement field from which the strain fields can be derived. The image acquisition consists on a stroboscopic procedure that allows us to observe the response of the sample under the applied load. One cycle is reconstructed from several pictures taken over several cycles [6].

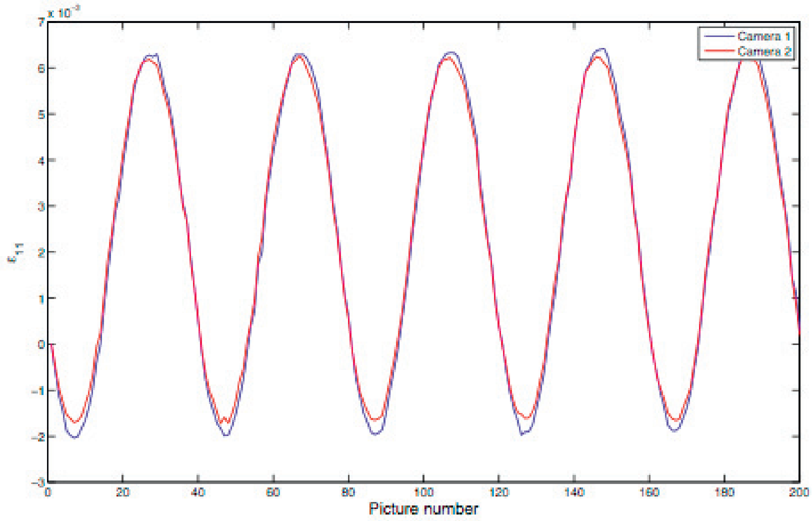

Figure 4 : Example of strain mesurement along the first machine axis using DIC. 5 cycles are reconstructed over a sequence of 10 000 cycles

Tests are force driven. Loadings are applied as sequences of 10 000 cycles. Between two sequences, pictures are taken at zero load (so that residual strains over the test are measured) and at maximum load in order to be able to follow the crack growth at the end of the test. The tested loadings include :

- in phase loadings
- out of phase loadings
- two blocks loadings (cumulative damage effects)

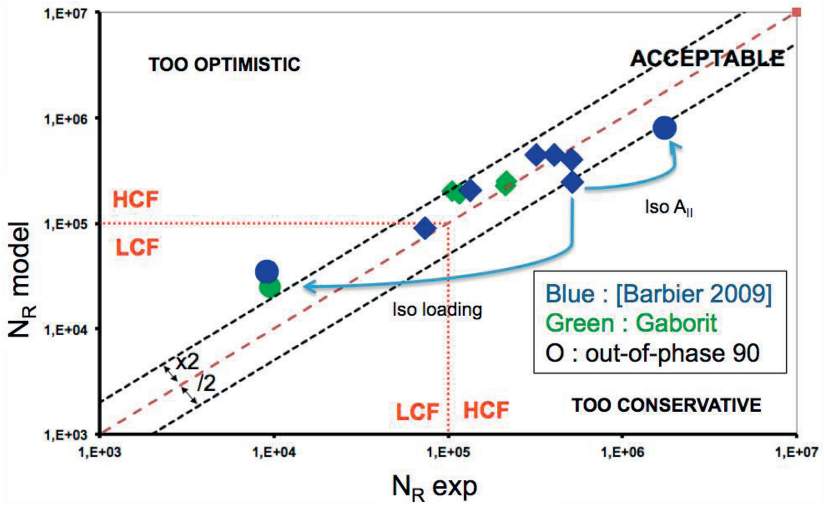

Figure 5 : Comparison between experimental results and prediction from the two scale damage model

The experimental results have been compared to the model prediction. In the HCF domain, model and experiments are in a good agreement. In the LCF domain, the model predicts a drop of the lifetime but the magnitude of order is not as accurate as in the HCF domain. However those tests are only under out of phase loadings (phase shift 180°). In that case the hypothesis of isotropic damage may not be valid.

5. Conclusion and perspectives

Experimental results on biaxial fatigue performed on cross shape samples are presented. Observation is done using a Digital Image Correlation calculation. The two-scales damage model, implemented in a code named "DAMAGE" provides good prediction of these experiments results. The current phD thesis aims to extend the prediction of the model suited for the High Cycle Fatigue domain to the Low Cycle Fatigue one.

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